Physics AUC, vol. 28, 1-11 (2018) **PHYSICS AUC**

Multifocal ignition of combustion chamber by subcritical streamer microwave discharge

BULAT P.V.[1], BULAT M.P.[1], DENISSENK OP.V.[2], UPYREV V.V.[3], VOLOBUEV I.A.[3,4]

[1] Baltic State Technical University "Voenmeh" D.F. Ustinov,
Saint-Petersburg, 190005, Russia
[2] Warwick University, Coventry, CV4 7AL, United Kingdom
[3] ITMO University, Saint-Petersburg, 197101, Russia
[4] Ltd. "VNH-Energo", Saint-Petersburg, 198035, Russia

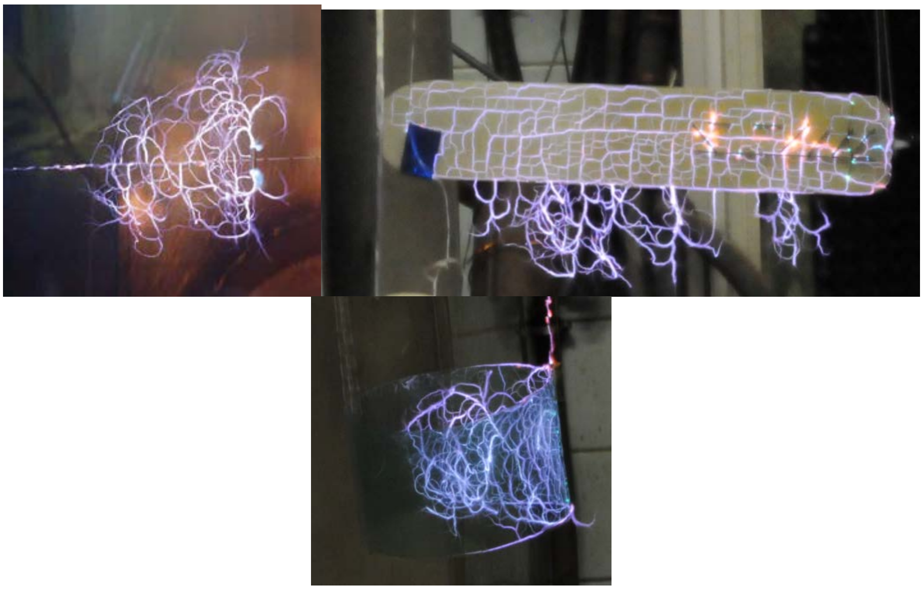
Abstract

The challenges facing the engine developers, aimed at improving the technical and operational characteristics, more stringent environmental standards, make the work aimed at increasing the efficiency of the ignition systems highly relevant. The aim of this paper is to study a new method for initiating a fuel mixture due to a subcritical microwave streamer discharge. This method seems promising, because it provides practically instantaneous ignition of the mixture in the entire volume. Here, the results of experiments using proposed method of ignitionare presented. Combustion process was recorded on high speed camera and compared with traditional ignition method. The possibility of volumetric ignition and a substantial increase in the completeness of fuel combustion is shown. A number of indirect signs indicate the absence of nitrogen oxides in combustion products. The results can be applied in the development of multi-volumetric volumetric ignition systems in combustion engines and power turbines.

Keywords: Microwave discharge, volumetric ignition, ignition system, streamers discharge, emission reduction.

Introduction

The purpose of this work is to study the possibility and efficiency of ignition of a fuel mixture by a so-called streamer discharge. The main facts about streamer discharges and the possibility of their use in the systems of initiation of combustion and detonation are given in the review articles[1, 2] and monograph [3]. Streamers are called discharges, consisting of a set of plasma channels, which form a chaoticgrid in space or on the surface (Figure 1). To form such a discharge, it is necessary that at some point in space the intensity of the electric field exceeds the so-called breakdown intensity. The threshold of breakdown depends on the pressure in the medium [4]. Streamer discharges are very stable and can be ignited in high-speed flows [5].



a) b) c)

Figure 1: Streamer discharge in open space (a), on a flat dielectric surface (b) and on a concave surface (c).

A large volume of research of streamer discharges [6] was performed at the Moscow Radio Engineering Institute of the Russian Academy of Sciences (MRTI). In particular, a method for initiating a discharge in a quasioptical microwave beam on the surface of a half-wave vibrator has been developed [7]. The vibrator serves as a resonator and in a small neighborhood increases the intensity of the electric field by one or two orders. This makes it possible to ignite discharges at an average strength substantially below the breakdown threshold. Depending on the magnitude of the electric field strength, it is possible to ignite discharges of various types [8]. They can have the character of diffuse plasma formation attached to the resonator. In this case, the field strength is insufficient to allow the plasma channels to go beyond the diffuse cloud. With an increase in the field strength, the plasma channels exit and form a streamer structure.

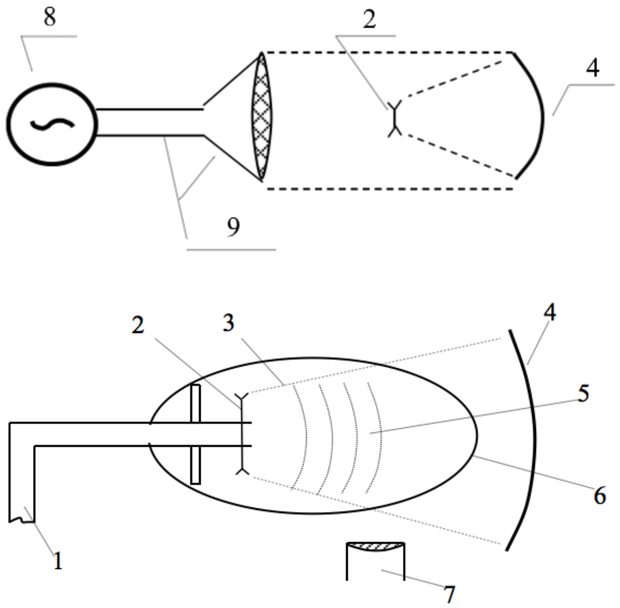
The high temperature in plasma channels has long attracted researchers as a way to initiate combustion under difficult conditions [9]: poor mixture [10], low temperatures, high flow velocity [11]. In particular, the concept of volumetric ignition is explored [12], when plasma formation occupies an appreciable volume of the combustion chamber [13]. As shown by the studies [14, 15], volumetric ignition of the fuel mixture is a promising way to initiate detonation and organize combustion in high-speed flows. The only drawback is the high energy consumption for creating a plasma discharge. The resonant method of initiating a discharge using a field with a subcritical level of tension developed by the staff of the MRTI RAS demonstrated energy efficiency exceeding that of traditional discharges [16] created by, for an example pulse lasers [17], by at least an order of magnitude [18].

In this paper, results of an experimental study of ignition of a propane-air mixture with a streamer discharge are presented. A comparison is made of the burning rate of a fuel mixture ignited by a streamer discharge and a conventional spark discharge, provided equal energy is supplied. With the help of a high-speed camera, the mechanism of ignition by a streamer discharge has been studied.

1 Experimental setup

1.1 Volumetric ignition of the fuel mixture

The scheme of the experimental setup is shown in Figure 2a. The installation includes a microwave generator MRTI RAS, which operates at a frequency of $f \approx 3 \cdot 10^9$ Hz or a long wavelength λ = 8.9 cm, with the duration of the microwave pulse τ_{imp} = 40 μs. The impulse is formed with the super capacitor, due to which high power in the discharge - 1 MW was provided.



a) b)

1 - Supply of propane-air fuel mixture; 2 - Initiator of microwave discharge; 3 - microwave beam; 4 - Focusing mirror; 5 - Front of the flame; 6 - Thin radio-transparent shell; 7 - photo recorder; 8 - Generator; 9 - The elements that form the microwave radiation.

Figure 2: Scheme of a laboratory installation - a microwave generator (a) and installation for the investigation of an attached streamer discharge (b).

Electromagnetic oscillations propagate along the elements forming a linearly polarizing quasi-optical microwave beam with a transverse diameter of 60 cm. The radiation is fed to the focusing mirror. In the region of the focus, the transverse dimension of the microwave beam is approximately 10 cm and has a characteristic length of about 15 cm. An attenuator is included in the elements forming microwave radiation, which makes it possible to change the power of the microwave beam in the range from10^2 Wto $\approx 10^6$W.The power was set such that the discharge transmitted 24 joules of energy to the substance.

Directly to the initiator is attached a rubber ball with a diameter of about 10 cm, filled with a mixture of propane and air. When a pulse with a duration of about 40 μs is applied to the initiator, an energy of about 1 J is applied (the maximum available pulse power is about 1 MW). In this case, within the ball runs a streamer discharge, igniting the mixture. As a result, the ball bursts.

1.2 Ignition of the fuel mixture by a surface streamer discharge

The experiment used the same plant (Figure 2b), but the focus is placed in a dielectric plate, which is attached to the discharge initiator. A rubber ball was put over the plate, which was filled with a mixture of propane and air. Experiments have shown that the streamer discharge runs towards the field at a speed of 10-15 km / s, repeating the shape of the surface. This speed is 3-4 times higher than the characteristic rate of development of the discharge in free space. The discharge can be ignited on the surface of the straight planar dielectric piece, and at the end of the cylindrical surface and the inner surface of the cylinder. The application of irregularities on the surface (a scratch, a dent) leads to the formation of a cord discharge along this defect.

2 Results

2.1 Comparison of ignition by spark and volumetric streamer discharge

The first experiment was conducted with a spark initiation of combustion of a stoichiometric mixture of air and propane. The air balloon was inflated with a fuel mixture to a diameter of about 10-15 cm and was ignited by an automobile candle. As a result, classical diffusion combustion developed (see the film in Figure 3).

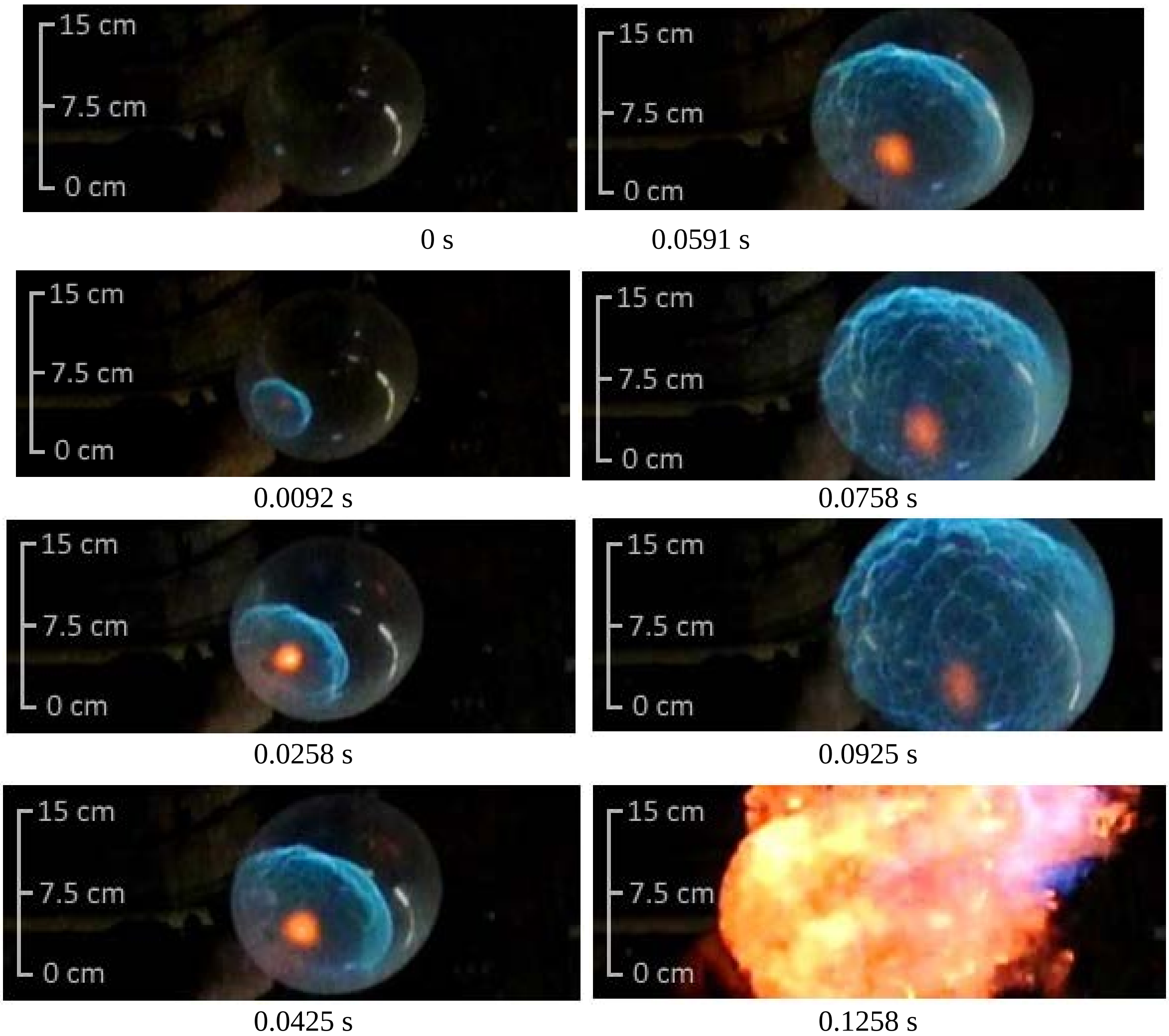
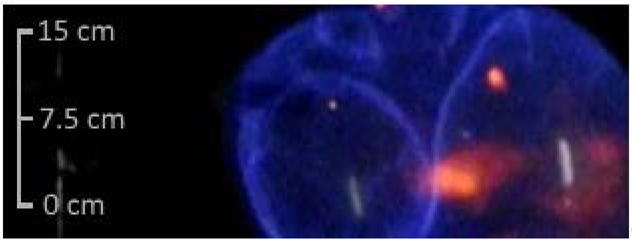


Figure 3: Burning of a ball filled with a stoichiometric mixture of propane and air, with spark ignition.

At the place of ignition, for a long time, a bright luminous spot of orange remained, characteristic of regions with a large temperature gradient, in which, mainly, nitrogen oxides are produced.

The flame front velocity measured with the camera was 1.5-2 m/s. The flame had a bluish greenish tint, which indicates the presence of yellow lines in the emission spectrum, which are characteristic for the emission of soot particles and nitrogen oxide. At the moment when the ball burst, a bright yellow turbulent flame was released, which continued to glow for another 0.1 seconds.

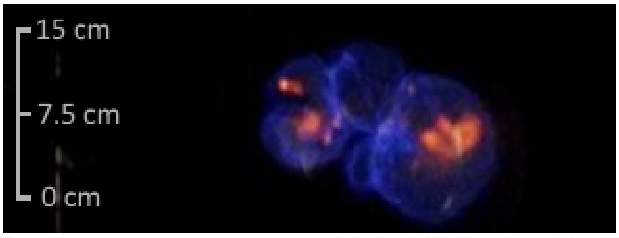
A similar experiment was carried out with the initiation of burning by a streamer discharge. To the initiator, as well as in the case of an automobile candle, energy was supplied in the amount of 24 J. However, the time of energy supply was only 40 μs, which is 1000 times less than during a spark discharge. The observed burning pattern (Fig. 4) radically differed from the case of spark ignition.



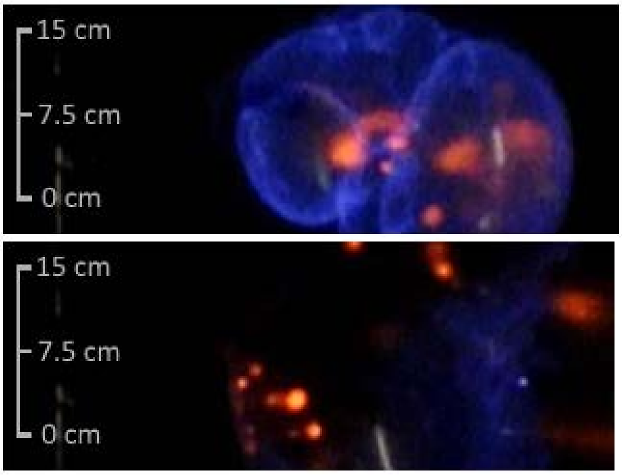
0 s

0.0258 s

0.0008 s0.0342 s



0.0092 s 0.0425 s



0.0175 s 0.0508 s

Figure 4 - Burning of a ball filled with a stoichiometric mixture of propane and air, with streamer ignition.

The velocity of propagation of the flame front was 6-10 m / s. The ball burst twice as fast as when spark ignited. The flame had an even purple color, characteristic of the combustion of pure natural gas. An orange spot did not appear. However, the front of the flame was strongly turbulent and numerous, so-called "hot" points formed on its fractures, from which detonation can develop. They are visible in the photos as red areas.

After the balloon burst, there was no ejection of the red flame, and there was no afterglow. This speaks in favor of the fact that propane burned completely.

For a detailed study of fast combustion, an experiment was performed (Figure 5), during which the survey was already conducted at a rate of 69,000 frames / s. On the first frame, a streamer discharge flash is visible. The speed of the camera is not enough to see the structure of the discharge, so another experiment was conducted later, when the video was recorded at a speed of 560,000 frames / s by high speed camera Phantom v2511. This experiment allowed to determine the fact that combustion begins to develop after the discharge is extinguished, and the flame front immediately has a strong turbulence.

2.2 Ignition of the fuel mixture by a surface streamer discharge

For a more thorough study of the ignition mechanism with a streamer discharge, experiments were carried out with a surface discharge ignited on a planar dielectric plate.

Experiments have shown that the streamer discharge runs toward the field at a speed of 10-15 km / s, repeating the shape of the surface, i.e. the rate of its development is 3-4 times greater than the speed of development of a streamer discharge in free space. Plasma channels are clearly visible (Figure 6). They are the sources of ignition. Although the discharge develops progressively in the direction from the initiator to the source of radiation, its propagation velocity is so great that ignition of the combustible mixture occurs immediately on the entire surface along which the discharge ran through (Figure 7).

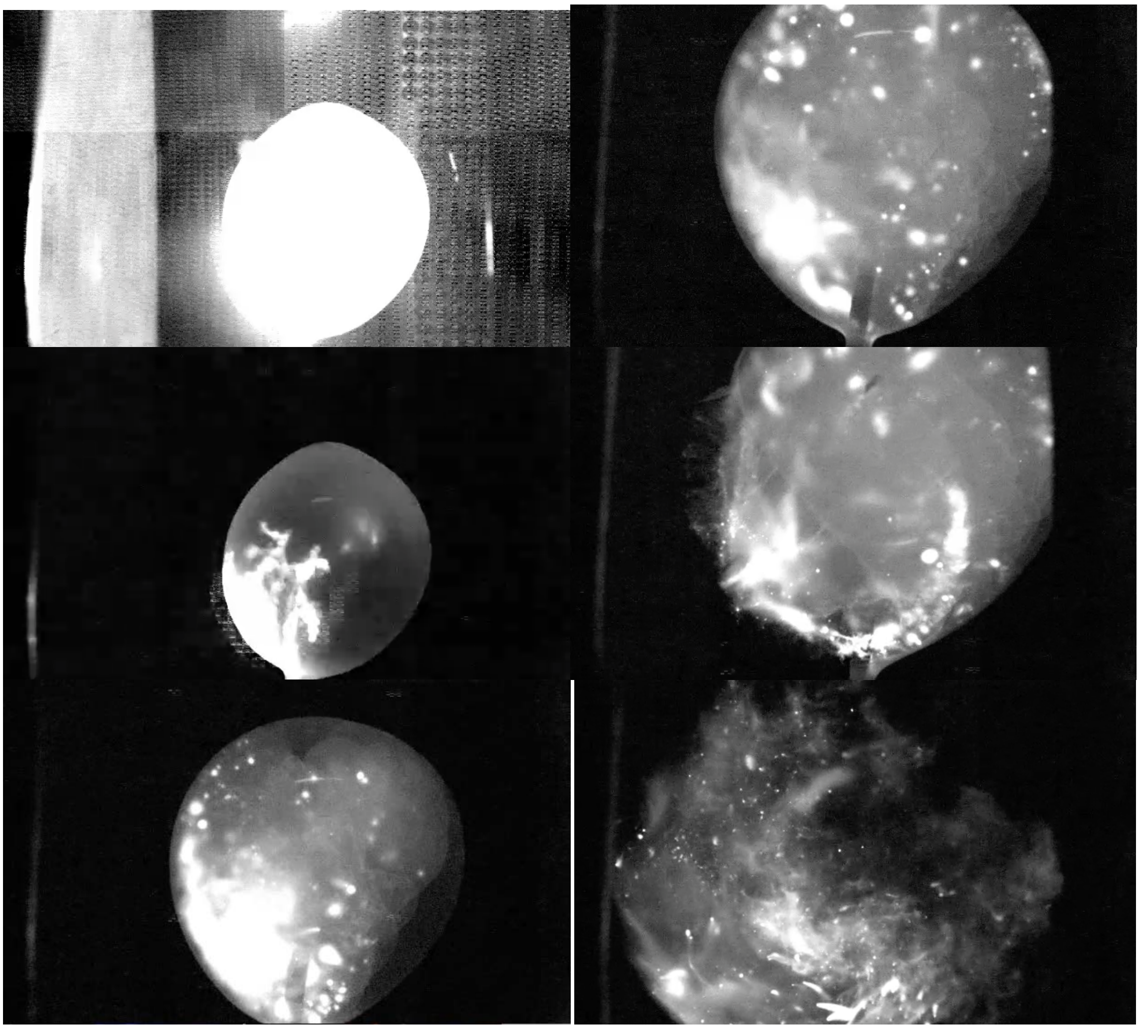
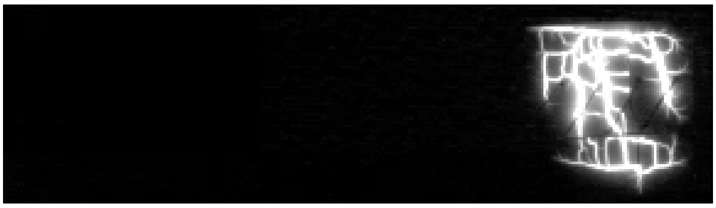
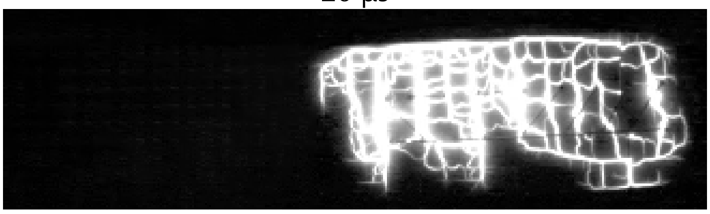


Figure 5: The ignition of a ball with propane streamer discharge. 69000 frames / s.



20 μs



40 μs

Figure 6: Development of a streamer discharge connected to a flat plate. The initiator on the right, sources of microwave radiation from above.

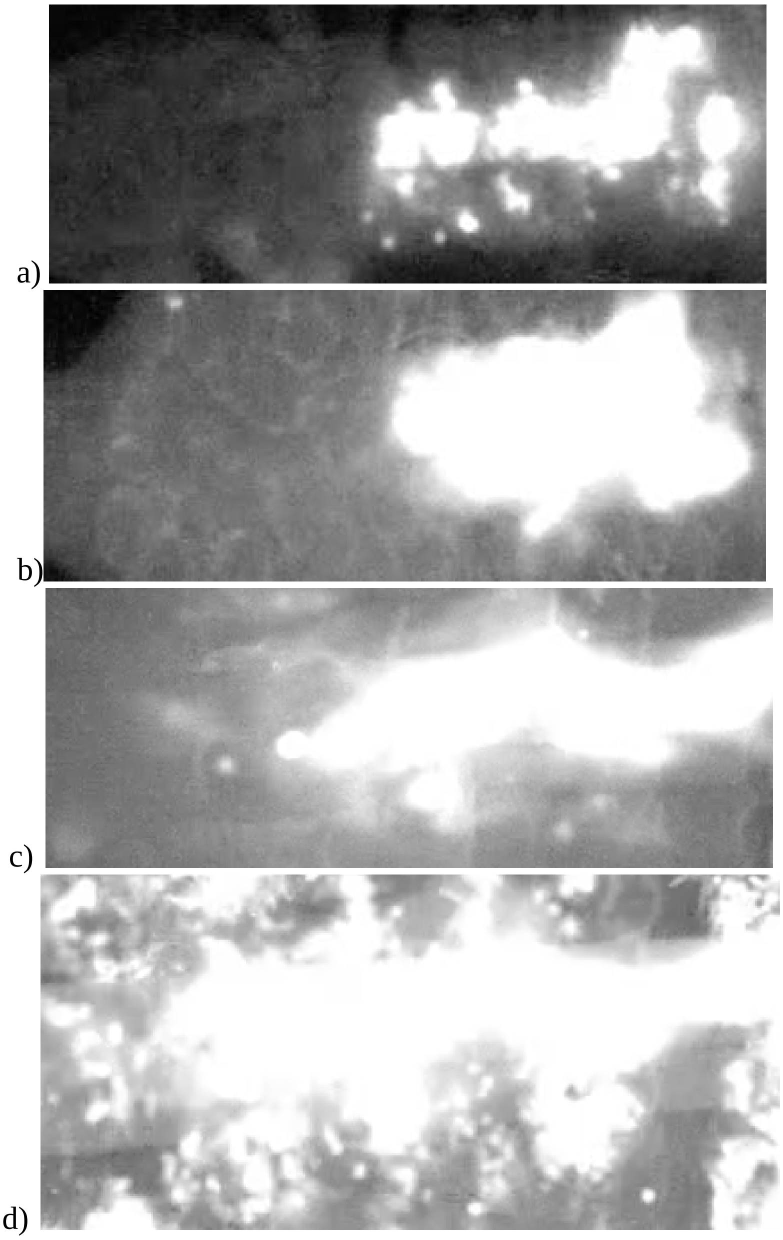


Figure 7: Ignition of the fuel mixture by a streamer discharge on a flat plate.

3. Discussion

The initiation of ignition with a streamer discharge radically altered the combustion pattern: the combustion rate and the completeness of combustion increased at times, no soot was formed. On the basis of indirect evidence (flame color and afterglow), it can be assumed that the nitrogen oxides NOx were released in a minimum volume, glowing orange areas, characteristic of large temperature gradients, were absent.

In addition, the analysis of the frames of the film made it possible to make the assumption that the ignition occurred immediately in a considerable volume, i.e. was determined not by thermal conductivity, but by some other mechanism.

Starting with the second frame, in Figure 5 we see how the burning region develops. Already at the initial moment of time it is distinguished by a strong turbulence, the front of the flame has a complex shape. In the nodes of the front in a large number of "hot spots" are formed. Their number first grows rapidly, and then remains approximately constant until the moment the ball bursts. From the "hot spots" spread strong waves of compression, which form new spurts of the front of the flame and new "hot spots".

Thus, it can be concluded that the streamer discharge, due to its developed spatial structure, immediately forms the shape of the flame front, which is most favorable for the transition of combustion to detonation. The appearance of many "hot spots" and severe ultraviolet (UV) radiation significantly (at times) increases the burning rate and the completeness of combustion.

Comparison of Figures 6 and 7 shows that although the ignition occurs after the streamer discharge has gone out, with a delay of about 50-100 ms, the flame forms immediately in the entire volume previously occupied by the streamer discharge. In Figure 7b, shock waves propagating from the ignition region are clearly visible. They propagate from the ignition region to the unreacted mixture, forming highly visible detonation fronts (Figure 7c). On the detonation fronts, new multiple "hot" points are formed - the foci of combustion, which themselves become sources of new detonation waves. Measurements performed on a frame-by-frame scan showed that the characteristic velocity of shock waves and detonation fronts in Figure 7 is more than 2 km / s.

Thus, it can be concluded that a streamer discharge, developing in a certain volume for a few tens of microseconds, has time to heat the gas in this entire volume to a temperature exceeding the ignition temperature of the fuel mixture during this time. The heating mechanism is shock-wave. The gas is heated by shock waves propagating from the streamers. Therefore, the ignition is of a volumetric nature.

Conclusion

A study was made of the initiation of combustion of a propane fuel mixture with air by means of a streamer discharge. The discharge was ignited by a quasi-optical microwave radiation beam on a resonator, which was a half-wave vibrator. The amplification of the electric field in the vicinity of the resonator by an order of magnitude made it possible to ignite the discharge at an electric field strength much lower than the breakdown energy. The ignition of a fuel mixture by a streamer discharge in free space and on the surface of a dielectric plate was investigated.

Studies have shown that at atmospheric pressure and room temperature in free space, the streamer discharge propagates at a speed of about 3-5 km / s. On the surface of the dielectric plate, the discharge propagation velocity increases to 10-15 km / s. Earlier such high discharge rates were not fixed. The discharge burns for 40-100 microseconds. The ignition of the fuel mixture occurs after the discharge has gone out. The delay is from 50 to 100 ms, which roughly coincides with the time of induction of the stoichiometric mixture of propane with air.

The ignition is of a three-dimensional nature; at the very initial moment of time, the flame is formed immediately over the entire volume to which the streamer discharge previously spread. Although combustion begins immediately over the entire volume, the glow is brighter at those points where the nodes of the streamer discharge were located. Frame-by-frame analysis of video captured by a high-speed camera, as well as image processing, showed that gas heating between the plasma channels of a streamer discharge is carried out by shock waves that propagate from plasma nodes in which plasma channels branch. The velocity of propagation of shock waves is more than 2.5 km / s. Subsequent combustion also occurs with the formation of shock waves that ignite a fuel mixture previously unaffected by the streamer discharge. The interaction of detonation waves leads to strong turbulence in the combustion zone and the formation of a number of "hot spots", which in turn become sources of new detonation waves.

The mechanism described above leads to an increase in the combustion rate by a factor of 4-5. The combustion is complete, NO_x oxides do not form.

Acknowledgement

The work was supported by the Ministry of Education and Science of the Russian Federation (agreement No. 14.574.21.0151, unique identifier of the project RFMEFI57417X0151).

Reference

1. Bulat P.V., Esakov I.I., Grachev L.P., Denissenko P.V., Bulat M.P., Volobuev I.A. Modeling and simulation of combustion and detonation by subcritical streamer discharge. Scientific and Technical Journal of Information Technologies, Mechanics and Optics, 2017, vol. 17, no. 4, pp. 569–592 (in Russian). doi: 10.17586/2226-1494-2017-17-4-569-592
2. Starikovskiy, A., Aleksandrov, N. (2013) “Plasma-assisted ignition and combustion.” Progress in Energy and Combustion Science 39. doi:10.1016/j.pecs.2012.05.003.
3. Fridman, A. and Kennedy, L. (2011) Plasma Physics and Engineering, Second Edition. Taylor and Francis, Boca Raton, FL. ISBN 978-1-4398-1228-0.
4. Khodataev K.V. Breakdown threshold in the microwave field at low and high pressures in electronegative gas mixtures. Technical Physics, 2013, vol. 58, no. 2, pp. 294–297. doi: 10.1134/S1063784213020126
5. Shibkov, V.M, Aleksandrov, A.A., Chernikov, V.A., Ershov, A.P., and Shibkova, L.V. (2009) “Microwave and Direct-Current Discharges in High-Speed Flow: Fundamentals and Applications to Ignition.” Journal of Propulsion and Power Vol 25 No. 1 pp. 123-137. doi: 10.2514/1.24803
6. Khodataev K.V. The nature of surface MW discharges // Proc. 48th AIAA Aerospace Sciences Meeting and Exhibition. Orlando, USA, 2010. Art. 2010–1378.
7. Esakov I., Grachev L., Khodataev K., Van Wie D. The linear 1151 electromagnetic vibrator as the initiator of electric breakdown of air in deeply subcritical field of quasioptical microwave beam // Proc. 49th AIAA Aerospace Sciences Meeting. Orlando, USA, 2011. Paper AIAA 2011–1151. doi: 10.2514/6.2011-1151
8. Aleksandrov K.V., Grachev L.P., Esakov I.I., Fedorov V.V., Khodataev K.V. Domains of existence of various types of microwave discharge in quasi-optical electromagnetic beams. Technical Physics. The Russian Journal of Applied Physics, 2006, vol. 51, no. 11, pp. 1448–1456.
9. Starikovskaia, S M. (2006) "Plasma assisted ignition and combustion." Journal of Physics D: Applied Physics: R265–R299.
10. Bak, M.S., Do, H., Mungal, M.G. Cappelli, M. A. (2012) “Plasma-assisted stabilization of laminar premixed methane/air flames around the lean flammability limit.” Combustion and Flame 159:3128–3137.
11. Pertl, F A, and J E Smith. (2009) “Electromagnetic design of a novel microwave internal combustion engine ignition source, the quarter wave coaxial cavity igniter.” Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 1405-1417.
12. Michael, J.B., Dogariu, A., Shneider, M.N. Miles, R.B. (2010) “Subcritical microwave coupling to femtosecond and picosecond laser ionization for localized, multipoint ignition of methane/air mixtures.” Journal of Applied Physics, 108 (9) Article Number: 093308 http://dx.doi.org/10.1063/1.3506401.

13. Chernyshev S.L., Skvortsov V.V., Ivanov V.V., Troschinenko G.A. A concept for generation and application of body- centered non-equilibrium discharge for initiation and intensification of fuel combustion in high-speed flows. AviatsionnayaPromyshlennost', 2013, no. 2, pp. 19–25.
14. Starikovskiy A., Rakitin A. Plasma-assisted ignition and deflagration-to-detonation transition // Proc. 53rd AIAA Aerospace Sciences Meeting. Kissimmee, USA, 2015. 19 p. doi: 10.2514/6.2015-1601.
15. Khodataev K.V. The ignition of the combustion and detonation by the undercritical microwave discharge // Proc. 32nd AIAA Plasmadynamics and Laser Conference. Anaheim, USA, 2001.
16. Sun, W. Won, S.H., Ombrello, T., Carter, C., Ju, Y. (2013) "Direct ignition and S-curve transition by in situ nano-second pulsed discharge in methane/oxygen/helium counterflow flame." Proceedings of the Combustion Institute Volume 34, Issue 1, 847-855 http://dx.doi.org/10.1016/j.proci.2012.06.104.
17. Michael, J.B., Dogariu, A., Shneider, M.N. Miles, R.B. (2010) "Subcritical microwave coupling to femtosecond and picosecond laser ionization for localized, multipoint ignition of methane/air mixtures." Journal of Applied Physics, 108 (9) Article Number: 093308 http://dx.doi.org/10.1063/1.3506401.
18. Khodataev K.V. The power effectivity of a microwave undercritical attached discharge, initiated by resonant vibrator // Proc. 43rd AIAA Aerospace Sciences Meeting and Exhibit. Reno, USA, 2005. P. 13341–13346.

Information about authors:

Pavel Viktorovich Bulat, PhD in physics and mathematics, PhD in economics, Scientific Supervisor of International Laboratory "Mechanics and energetic systems",, ITMO University, Saint Petersburg, 197101, Russian Federation

Mikhail Pavlovich Bulat, PhD in Technical Sciences, Science Fellow in International Laboratory "Mechanics and energetic systems", ITMO University, Saint Petersburg, 197101, Russian Federation

Petr Vasilievich Denissenko, PhD in applied mathematics, engineer, ITMO University, Saint

Petersburg, 197101, Russian Federation; researcher, University of Warwick, Coventry, CV4 7AL, United Kingdom,

Vladimir Vladimirovich Upyrev, Science Fellow in International Laboratory "Mechanics and energetic systems", ITMO University, Saint Petersburg, 197101, Russian Federation

Igor Alekseevich Volobuev, Science Fellow in International Laboratory "Mechanics and energetic systems", ITMO University, Saint Petersburg, 197101, Russian Federation